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TITLE DEVELOPMENT OF HIGH-TEMPERATURE LIQUID-METAL HEAT PIPES FOR ISOTHERMAL IRRADIATION ASSEMBLIES

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DEVELOPMENT OF HIGH-TEMPERATURE LIQUID METAL HEAT PIPES FOR ISOTHERMAL IRRADIATION ASSEMBLIES

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ABSTRACT

This paper describes the development of high-temperature heat pipes and their operating performance using liquid metal working fluids to provide high heat transfer assemblies for in-pile testing of UO_2 fuel. The fuel assembly consists of thin UO_2 wafers sandwiched between molybdenum discs, and is one of the components of the space nuclear reactor electrical power plant currently under development. The intended operation of the heat pipes is to control the temperature of the UO_2 irradiation experiment in the Experimental Breeder Reactor (EBR-II). This application involves vertical operation in a gravity-assist mode, with the evaporator end down. Heat pipe construction and preparation techniques are described. Laboratory tests were made and the performance characteristics determined. Test results are compared with calculated heat transfer limits.

INTRODUCTION

Components of the space nuclear electrical power plant are currently under development at Los Alamos National Laboratory (1). This power plant system will have the capability to deliver 10-100 kW_e and will be a compact source for large earth orbiting satellites. Part of the power plant consists of a nuclear reactor for generating heat; heat pipes are utilized to transfer the thermal energy from the reactor to the power conversion system. The space power plant is being designed for a seven-year continuous operation, thereby requiring a high degree of reliability of all subcomponents. To design the core components to satisfy these requirements, it is necessary to conduct in-pile tests of the space reactor fuel configurations. Accommodation of fuel swelling is usually a major area of reactor fuel element design.

The fuel material for the space reactor power supply will be UO_2. There is a lot of data on the behavior of UO_2 under irradiation for a variety of temperatures and burnup conditions. The moderately low fuel temperature (1600-1700 K) and low fuel burnup (4%) in the space power reactor will result in a moderate fuel swelling (7-8%), which should be readily accommodated. However, the fuel configuration of the space reactor, namely layers of UO_2 sandwiched between molybdenum wafers that form the major heat conduction paths to the core heat pipes, is so different from the typical pin geometry that it was considered necessary to conduct some in-pile testing of this geometry (2). The in-pile tests for the space reactor fuel will be conducted in the EBR-II because, like the space reactor, it is a fast reactor. The neutron fluxes cover a range where, with some enrichment changes, a seven-year-equivalent fuel burnup could be accelerated down to less than two years.

IN-PILE TEST OF UO_2 FUEL (3)

The space nuclear electrical power plant fuel in-pile test is planned for Argonne National Laboratory's EBR-II reactor at Idaho Falls. Two capsules are tentatively planned to be tested in row 7 (possibly 6) of the reactor. The experiments are designed to provide data on fuel swelling at the similar temperature conditions the fuel will experience in the space power reactor. Data will also be obtained on the heat transfer mechanism between fuel, fin and heat pipe; fuel migration, if it occurs; and chemical compatability of fuel, fin, and heat pipe materials.

The basic design of the fuel irradiation capsule is shown in Fig. 1. The experimental fuel is contained in four insulated bays on the evaporator end of the heat pipe. The heat pipe will use lithium or sodium as its working fluid and neon as a buffer gas. The fuel container is held in place on the 15.9-mm-diam heat pipe by the molybdenum heat transfer fins. The fins, which sandwich the fuel wafers, are attached to the heat pipe in the same manner as designed for the space power plant. A threaded length of the heat pipe is planned for the condenser section of the heat pipe that threads into a thin-wall niobium cylinder. This niobium cylinder is part of the first encapsulation of the fuel container and heat pipe assembly. A vacuum section surrounds the fuel container section (evaporator) of the heat pipe and is separated from the condenser section by a seal. This allows for a low neon gas pressure in the condenser region to ensure heat transfer through the threaded section.

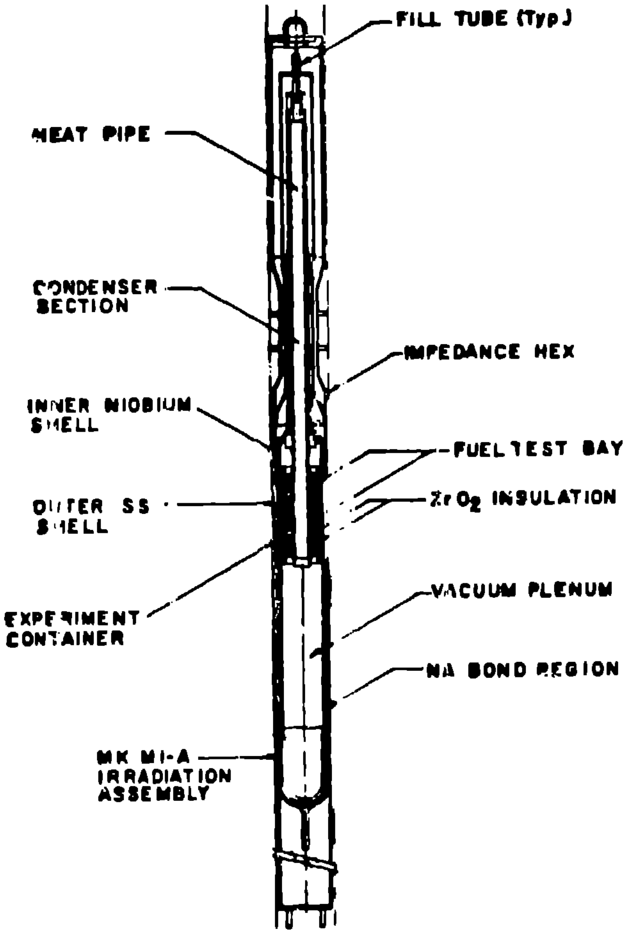

Fig. 1. EBR-II irradiation experiment capsule.

Between the inner niobium shell and the outer 316 SS container, a sodium fill is utilized to bond the condenser section and the buffer gas region of the heat pipe to the sodium coolant of the EBR-II. The sodium fill also permits good thermal control of the outside of the niobium vacuum chamber in case of fuel melt. Various fill/evacuation tubes are located at appropriate places in the assembly. Reactor coolant is forced inwards to the condenser section by an impedance hexagon to provide proper coolant for the heat pipe condenser.

Proper operation of the temperature control feature of the gas-filled heat pipe that cools the UO_2 fuel wafers depends on the thermal conductance from the threaded condenser section to the EBR-II reactor coolant. Calibration testing of the heat pipe assembly will provide experimental data points to verify the analytical model developed to study the heat removal capability of the condenser section.

DEVELOPMENT OF THE PROTOTYPE IN-PILE HEAT PIPES

The design and fabrication requirements imposed on the in-pile heat pipe are similar to those for the core heat pipes of the space power plant. There are differences in the operational characteristics, however. The radial power density from the fuel into the heat pipe varies from test bay to test bay, generally exceeding the value of 1.2 MW/m^2 expected in the reactor core, with a maximum of 2.1 MW/m^2. The required heat throughput is 8.3 kW and the operating temperature has been set at 1500 K.

A specific type of wick structure is required to achieve the high heat transfer performance of the in-pile heat pipes that operates in a gravity-assist mode with an inert buffer gas present for thermal control. This wick must be designed to optimize the internal dimensions for the maximum performance allowed by the heat pipe limits. Of these limits, the liquid entrainment limit was determined to be the governing one for the in-pile test heat pipe assembly (4). The entrainment limit is a result of shear interaction between the counterflowing liquid and the vapor stream. The shear stress exerted by the vapor on the liquid prevents the liquid from returning to the evaporator, and the result is a dryout in the wick in the evaporator.

Fabrication

Two prototype molybdenum heat pipes assemblies were constructed and tested, one with sodium as the working fluid and one contained lithium. Molybdenum was selected as the heat pipe material because of its compatibility with the UO_2 fuel and high temperature operation of the fuel-heat pipe system (1500 K).

Both heat pipe assemblies were constructed in the same manner (Fig. 2). The heat pipes are 432 mm in length, with an outside diameter of 15.9 mm. A two-layered screen wick structure, one layer of fine mesh screen and the other of coarse mesh, was tested (Fig. 3). The fine screen layer (150 mesh molybdenum) mesh was placed against the inner wall of the heat pipe; it is used for fluid distribution. The coarse mesh screen, also molybdenum, was placed over the first layer so that it was next to the vapor passage. This layer acts as a protective cover for the gravity return of the condensate, thereby minimizing the entrainment of the returning fluid. Curves calculated by Prenger(5) giving the entrainment limits for various mesh sizes are shown in Fig. 4. Although the 8 mesh screen shows the best expected performance, its wire diameter (0.8 mm) made fabrication of a wick structure extremely difficult. No satisfactory or acceptable wick structures were fabricated with the 8 mesh. The 20 mesh screen with 0.30 mm diameter wire was used to fabricate the prototypical heat pipes. This material was deemed to give the best compromise between ease of fabricability and performance safety margin above the required 8.3 kW throughput.

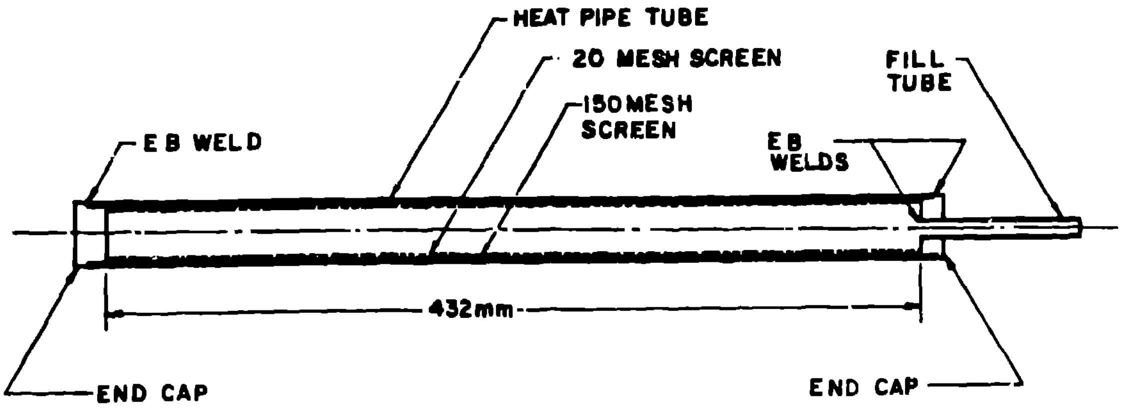

Fig. 2. EBR-II prototype heat pipe assembly.

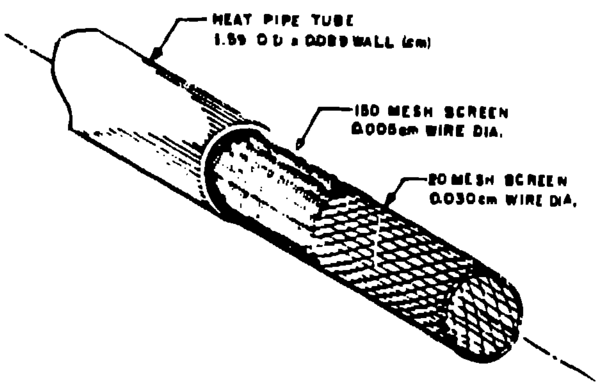

Fig. 3. EBR-II heat pipe screen tube assembly.

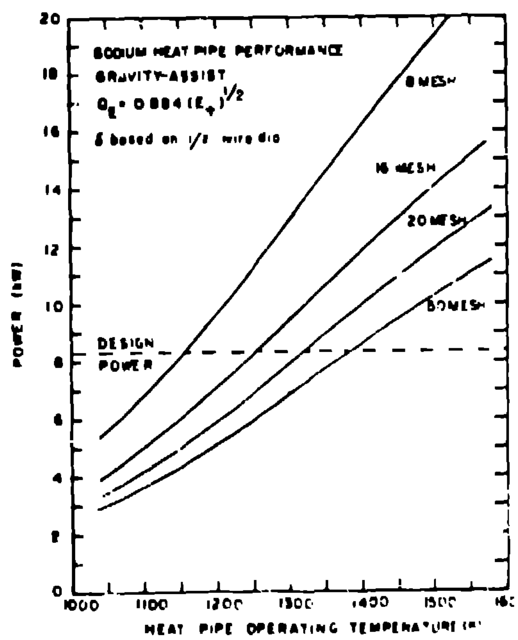

Fig. 4. Entrainment limits for EBR-II heat pipe.

The heat pipe materials were cleaned by full immersion in either sodium or lithium and baked overnight at 1100 K, followed by a rinse in ethanol. This procedure was followed by a high-vacuum firing to 1700 K for 2 h. The end caps were electron-beam-welded in place, and each pipe was then charged with a working fluid by vacuum distillation.

A schematic diagram of the vacuum distillation is shown in Fig. 5. The stainless steel distillation chamber contains multi-wrapped 100 mesh stainless steel screen in the inside wall to provide more surface area for evaporation and prevent slugging of the liquid to the top of the container. This distillation chamber is heated by rf induction. A set-volume chamber is attached to the distillation chamber with a stainless steel tube that extends through the lithium or sodium pool. The transfer tube and chamber are sized to furnish a volume of fluid sufficient to fill the wick structure plus form a 20-mm-long pool. A secondary stainless steel transfer tube leads from the bottom of the set-volume chamber to the heat pipe. The chilled heat sink is placed on the tubing just below the chamber to act as a valve to prevent the liquid metal from draining out of the chamber during distillation.

The total operation of transferring the working fluid from the still chamber to the heat pipe is as follows:

- A vacuum is pumped in the total system while the liquid metal pool is heated and degassed. The temperature is increased, and once distillation starts, the valve to the vacuum pump is closed. Distillation is complete when the volume from the chilled heat sink to the top of the transfer tube is filled with the distillate.

- The distillation chamber is cooled to approximately 100 degrees above the melting point of the sodium or lithium.

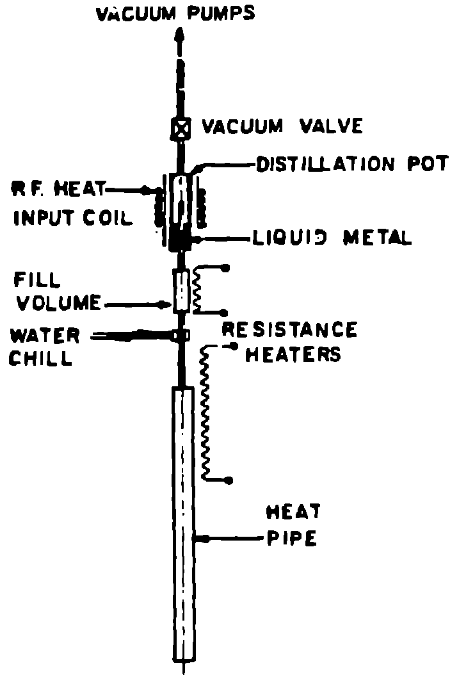

Fig. 5. Vacuum distillation set-up.

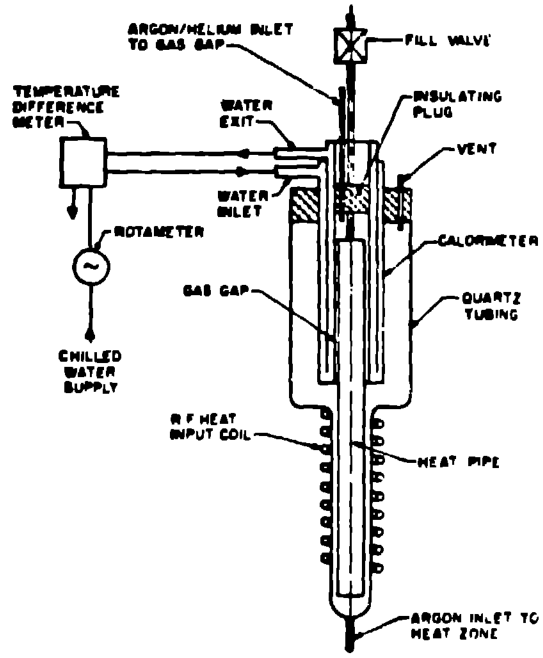

Fig. 6. EBR-II prototype heat pipe test configuration.

- The heat sink is removed and the heat pipe, 6.35-mm-diameter transfer lines, and the set-volume chamber are heated above the melting point of the working fluid, allowing the liquid to drain by gravity head into the heat pipe.

- The total system is backfilled with argon and the distillation system is removed and replaced by a valve.

- The heat pipe assembly is then attached to a vacuum pumpout station, and the argon gas is removed. The valve is closed, and the prototype heat pipes are ready for wet-in and subsequent testing.

TESTING OF PROTOTYPE EBR-II MOLYBDENUM HEAT PIPES

To make performance measurements of these heat pipes, it was necessary to construct a calorimeter facility. This facility provides an inert gas environment for the heat pipe and a variable-conductance gas gap in the heat rejection section, while holding a relatively low thermal-leakage path in the evaporator section of the heat pipe. To accomplish this, a dual gas flow calorimeter system, as shown in Fig. 6, was constructed. The figure shows a water-cooled gas-gap-calorimeter partly enclosed in a quartz envelope. The calorimeter is centered by an alumina insulator support, which includes a vent for the inert gas. The heat pipe's position can be changed to vary the lengths of the evaporator and/or condenser sections. Heat is supplied by an rf induction coil. The heat-input section of the system contains slowly flowing argon, which is introduced at the bottom of the quartz envelope. The argon exits through the insulator support. This arrangement tends to minimize the thermal loss to the quartz tube surrounding the evaporator.

Heat rejection to the calorimeter in the condenser section of the heat pipe is controlled by adjusting the ratio of argon to helium in a separate inert gas flow system. This gas mixture is introduced into the gap by a feed line through the insulator that centers the heat pipes. The gas flows slowly through the gap region, and eventually leaves the system through the same vent used to complete the argon flow circuit.

A temperature-difference meter and water-flow meter are used to measure the power transmitted by the heat pipe into the water flowing through the calorimeter. Heat pipe temperature is measured by optical pyrometry at the evaporator exit (that is, the region between the induction coil and calorimeter).

Performance testing of both the sodium and lithium-filled heat pipes has been conducted using a 100-mm-long rf induction coil to provide heat input. This coil length simulates the total heat input zone of the four fuel bays on the EBR-II heat pipe assembly. Axial heat transfer measurements were made at operating temperatures from

1000 to 1425 K, and heat transfer limits were determined for these systems. Data points showing the maximum heat transfer capability of the sodium heat pipe system are displayed in Fig. 7. The results show the sodium heat pipe exceeded the predicted entrainment curve up to a heat transfer rate of 7.7 kW at 1300 K. The limit point obtained at 1380 K indicates a decrease of performance at this temperature. It is believed that this reduced performance was caused by damage to the fine screen caused by testing to the wick dryout conditions that occur when a limit is reached.

The performance test results of the lithium heat pipe system are shown in Fig. 8. The measured heat transfer capability of the lithium heat pipe also exceeds the predicted curve for entrainment and shows a heat transfer rate of 10 kW at 1425 K. The 100-mm-long rf induction coil arrangement on the lithium heat system produced a radial heat flux average of 2.1 MW/m^2. Subsequent power density tests were conducted on the lithium prototype heat pipe by reducing the length of the heat input zone until a radial heat-input flux limit was determined. An input power density of 3.6 MW/m^2 at a temperature of 1375 K was achieved.

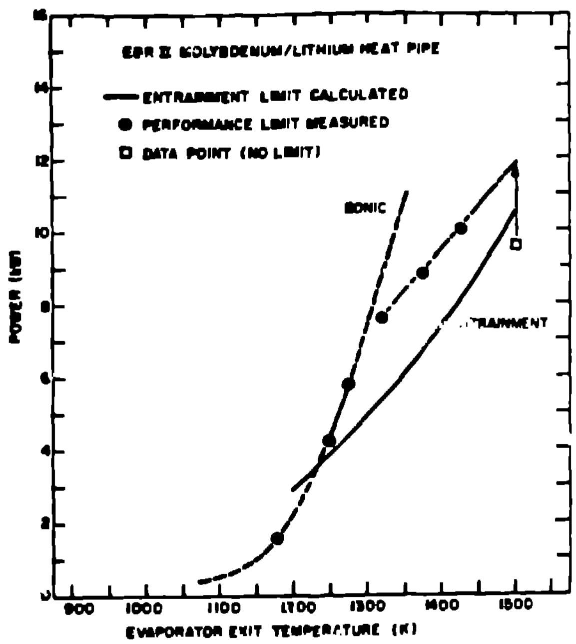

Fig. 8. Lit heat pipe performance.

CONCLUSIONS

A two-layer wick structure, one layer of fine mesh screen for distribution and a coarse layer of screen for protection of the gravity return fluid, has operated satisfactorily with sodium and lithium working fluids. The fabrication and testing of molybdenum/lithium heat pipes to provide high heat transfer assemblies for EBR-II in-pile testing of UO_2 fuel has been demonstrated. These heat pipe assemblies have performed well beyond the predicted limits for high heat transfer at high temperatures (i.e., 10 kW at 1425 K), and molybdenum/lithium heat pipes can withstand high power input densities (3.6 MW/m^2), almost twice the maximum requirement for the EBR-II fuel tests (2.1 MW/m^2).

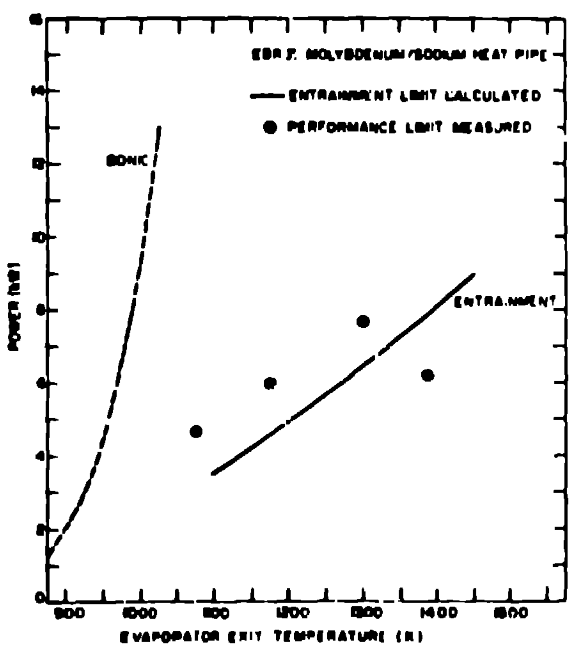

Fig. 7. Sodium heat pipe performance.

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